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KNOCK-LIMITED POWER OUTPUTS FROM A CFR ENGINE USING INTERNAL COOLANTS

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SUMMARY

An investigation was conducted to determine the knock-limited power obtainable by injecting water solutions of monomethylamine and dimethylamine as internal coolants into a CFR engine using AN-F-28, Amendment-2, fuel. Approximately saturated solutions were used which resulted in 32 percent by weight of monomethylamine in water and 27 percent by weight dimethylamine in water. The internal coolants were injected in the following proportions: water and the monomethylamine-water solution, 0.25 and 0.50 pound per pound of fuel; dimethylamine-water solution, 0.25, 0.50, and 0.75 pound per pound of fuel. In addition, a test was conducted with 0.50 pound dimethylamine-water solution per pound of fuel to determine the effect on engine performance of increasing the exhaust back pressure at high power outputs.

During the investigation, an indicated mean effective pressure of 967 pounds per square inch was attained at a fuel-air ratio of 0.092 when using a 0.75 pound dimethylamine-water solution per pound of fuel. For fuel-air ratios between 0.05 and 0.10, increasing the exhaust pressure had little effect on the knock-limited indicated mean effective pressure.

INTRODUCTION

The effect of injecting water into the intake-air system of an aircraft engine has been investigated by many laboratories. These investigations show that considerable increases in knock-limited power (references 1, 2, and 3) and temperature-limited power (references 4 and 5) are possible. Additional improvements in performance have been noted when mixtures of water and water-soluble compounds rather than water alone were used. Various laboratories have tested methyl and ethyl alcohol; Heron and Beatty (reference 6) tested isopropyl alcohol; the laboratories of Shell Development Company tested monomethylamine, finding it much more effective than methyl alcohol; and the laboratories of the NACA tested methyl alcohol, ethyl alcohol, ammonium hydroxide, monomethylamine, dimethylamine, and trimethylamine. (See references 7 and 8.) The use of water-soluble as well as fuel-soluble antiknock additives can therefore be applied toward the improvement of aircraft-engine performance.

Tests of three aliphatic amines in a CFR engine have been conducted at the NACA Aircraft Engine Research Laboratory as part of a general investigation of the antiknock effectiveness of internal coolants. The preliminary tests, which are presented in reference 8, indicated that monomethylamine-water and dimethylamine-water solutions are extremely effective in raising the knock-limited performance of AN-F-28 fuel. The range of operation of those tests, however, was limited to a fuel flow of 30 pounds per hour and an inlet-air pressure of 150 inches of mercury absolute. After the limits were raised to a fuel flow of 80 pounds per hour and an inlet-air pressure of 225 inches of mercury absolute, additional tests were run during which two four-hole cylinders were cracked at an indicated mean effective pressure of 700 pounds per square inch. The research project was continued during May and June 1944 after a specially machined two-hole cylinder had been obtained. Data obtained with the new cylinder and the extended fuel-flow and air-flow limits are presented herein.

ENGINE AND AUXILIARY EQUIPMENT

A standard CFR high-speed crankcase equipped with copper-lead main bearings, a thick walled wrist pin, and an extra heavy aluminum piston was used for these tests. The cylinder was simiiiar to a standard CFR casting except that the bouncing-pin hole was tapped with an 18-millimeter spark-plug thread at an angle of 25° to the vertical and the inside corner between the cylindrical wall and the flat-top head was machined with a 1/4-inch fillet to prevent stress concentration. Sodium-cooled exhaust and intake valves were installed. The 100-horsepower dynamometer was connected to the engine by means of a coupling and a bell flange bolted directly to the engine flywheel.

The fuel-flow and air-flow systems were the same as described in reference 8 except that a two-cylinder injection pump delivered fuel to the manifold. The amine solutions were forced directly from the supply drum to the rotameter by a low-pressure air supply and then passed through a circulation pump and a cooler to a high pressure injection-pump. The internal coolant was intermittently injected into the intake manifold through a high pressure nozzle beginning at 110° A.T.C. on the intake stroke. When water was used for the coolant, it was taken directly from the city mains to the rotameter measuring the internal-coolant flow.

A dual combustion-air system was installed whereby inlet-air pressures up to 190 inches of mercury absolute were obtained with a pressure regulator; inlet-air pressures from 190 to 225 inches of mercury absolute were obtained by throttling directly from the air supply. Air measurements were taken as described in reference 8 except that the high orifice differential pressures were read on a manometer containing tetrabromoethane instead of water.

A special spark plug inserted in the slanted top cylinder hole ignited the charge. The same spark plug was used for all tests and did not require cleaning during the tests. Knock was detected by a magnetostriction pickup unit and was recorded on a cathode-ray oscillograph.

A surge tank with a volume of $2\frac{1}{4}$ cubic feet was placed in the exhaust line very close to the engine. The surge tank gave a smooth control on the exhaust back pressure and reduced surging when atmospheric back pressure was desired.

TEST PROCEDURE

The internal coolants tested were: (1) water, (2) a solution of 32 percent by weight monomethylamine in water, and (3) a solution of 27 percent by weight dimethylamine in water. The amine-water solutions were obtained commercially and were of a technical grade.

Each test consisted of a series of knock-limited runs covering the normal range of fuel-air ratios. A few of the tests were cut short because the inlet-pressure limit of 225 inches of mercury absolute or the fuel-flow limit of 80 pounds per hour was reached. During all tests the following engine conditions were maintained constant:

Engine speed, rpm	2500
Compression ratio	7.0
Spark advance, deg B.T.C.	30
Inlet-air temperature, °F	250
Coolant temperature, °F	250
Oil temperature, °F	150

The ratio between fuel flow and internal-coolant flow was maintained by using a rotameter in each line and by proportionately changin the two flows. The fuel flow was checked with an automatic fuel-weighing stand. The fuel rotameter was calibrated against the fuel-weighing stand, and the coolant rotameter was similarly calibrated for each internal coolant. A single batch of AN-F-28, Amendment-2, fuel was used for all tests.

PRESENTATION OF RESULTS

The knock-limited indicated mean effective pressure, the inlet-air pressure, the indicated specific fuel consumption, and the indicated specific liquid consumption as functions of fuel-air ratio are presented in figures 1, 2, and 3 for straight fuel and for fuel plus the internal coolants added in the proportion of 0.25, 0.50, and 0.75 pound per pound of fuel. All contributions to the heat of combustion by the internal coolants were entirely neglected when the fuel consumptions were computed. All tests were run at approximately atmospheric exhaust pressure except one which was run at an exhaust pressure equal to half the inlet-air pressure. The results of this test, in which 0.50 pound dimethylamine solution was injected per pound fuel, are presented in figure 3. The relative powers resulting from the use of internal coolants were calculated from the curves in figures 1 to 3 and are given for several fuel-air ratios in table I.

The curve for straight fuel shown on figures 1 to 3 represents the average of seven tests, one of which was run on the same day as one or more of the internal-coolant tests. It was necessary to average these seven curves because they were not in close agreement, presumably because of the effect on the engine of the extremely high powers that were attained between the check tests. The maximum variation from the mean curve of indicated mean effective pressure was about 12 pounds per square inch near the stoichiometric-mixture ratio and decreased to about 3 pounds per square inch at a fuel-air ratio of 0.105 and higher.

The power curves in figures 1(a) and 2(a) demonstrate that with water the greatest power increases were obtained at or near the stoichiometric-mixture ratio. The amine solutions, on the other hand, gave their greatest increases in the rich-mixture region. For each internal coolant-fuel ratio, the amine solutions allowed higher knock-limited powers and lower indicated specific fuel consumptions at fuel-air ratios below 0.09 than did water. Except for a small region around the stoichiometric-mixture ratio, the addition of 0.25 pound of either amine solution permitted greater knock-limited powers than did the addition of 0.50 pound of water per pound of fuel.

The injection of 0.75 pound dimethylamine-water solution per pound fuel permitted the attainment of a knock-limited indicated mean effective pressure of 967 pounds per square inch, corresponding to 3.05 indicated horsepower per cubic-inch displacement, at a fuel-air ratio of 0.092. Completion of the test was prevented by the failure of a cylinder stud; the resulting vibration of the cylinder cracked the intake manifold. The engine, which had undergone 55 hours of operation since an overhaul, was inspected and the following conditions were noted:

1. The aluminum piston was quite clean and the rings were all free with no filling of the oil slots. (See fig. 4.)

2. The cylinder showed about 0.001 inch of wear throughout the entire length of ring travel.

3. There was excessive wear of the rings, which were of the keystone type used in the F-4 rating engine. The top compression ring was worn so much that its compressed gap increased 0.029 inch in addition to the increase permitted by the cylinder wear. The increases in the compressed gap of the other rings were slightly less.

4. The exhaust-valve crown was pitted and the stem was rusted and scuffed, but its seat was in fairly good condition. The intake valve was unaffected. (See fig. 4.)

Additional tests were undertaken after larger cylinder studs, a new intake manifold, and a new piston had been installed. The cylinder wall failed at an indicated mean effective pressure of 895 pounds per square inch during a test using 0.75 pound dimethylamine-water solution per pound fuel.

In the high-power ranges reached in these tests, the knock limit became quite broad and was hard to discern. In one instance the boost was accidentally increased 20 pounds per square inch above the pressure where knock began, and the ensuing knock trace on the oscilliscope did not seem unduly heavy. No preignition was encountered during the tests. Afterfiring occured only in the tests using 0.75 pound dimethylamine-water solution per pound fuel and 0.50 pound monomethylamine-water solution per pound fuel in the fuel-air-ratio ranges from 0.046 to 0.080 and from 0.074 to 0.085, respectively. During similar tests reported in reference 8, much afterfiring and preignition occured, as well as frequent spark-plug failures. The minimization of these difficulties may have resulted from the use of a different type cylinder, spark plug, or both.

Increasing the exhaust back pressure had little effect on the knock-limited indicated mean effective pressure at fuel-air ratios between 0.05 and 0.10, as shown in figure 3. For fuel-air ratios higher than 0.10, rough running and severe decreases in power output as compared with the atmospheric back-pressure test were observed.

The exhaust temperatures were measured for the test using 0.50 pound dimethylamine-water solution per pound fuel and for one of the straight-fuel check tests. These temperatures are plotted against fuel-air ratio in figure 5. Although the knock-limited power obtained in the test using dimethylamine ranged from 1.6 to 3.2 times that obtained with straight fuel, the exhaust temperatures remained lower except in the lean region. There is reason to believe that the temperature readings are low inasmuch as the thermocouple had only a single shield to prevent radiation, but this error should not affect the relative position of the two curves. The thermocouple and the shield were destroyed when the engine was operating at a knock-limited indicated mean effective pressure of about 800 pounds per square inch.

The required indicated specific liquid consumptions, for the powers attained, can be estimated for the internal coolants from figure 6. For a given knock-limited indicated mean effective pressure, 0.25 pound of the amine solutions gave appreciably lower indicated specific liquid consumptions than did either 0.25 or 0.50 pound of water. For each rich-mixture range of knock-limited performances, the following combinations of internal coolants and coolant-fuel ratios were observed to give the lowest indicated specific liquid consumptions:

imep range (lb/sq in.)	Corresponding minimum islc range (lb/hp-hr)	Internal coolant	Internal coolant-fuel ratio
Below 220	0.44 to 0.53	None	--------
220 to 370	0.53 to 0.63	Monomethylamine solution	0.25
370 to 440	0.63 to 0.71	Dimethylamine solution	.50
440 to 960	0.71 to 1.10	Dimethylamine solution	.75

The steep upward slant of the power curves for the tests using 0.50 and 0.75 pound of amine solution per pound of fuel indicates that still higher powers are feasible. (See figs. 2, 3, and 6.)

SUMMARY OF RESULTS

The results of knock-limited tests of monomethylamine-water and dimethylamine-water solutions as internal coolants in a CFR engine may be summarized as follows:

1. When 0.75 pound dimethylamine-water solution per pound of fuel was used, a knock-limited indicated mean effective pressure of 967 pound per square inch, corresponding to 3.05 indicated horsepower per cubic-inch displacement, was attained at a fuel-air ratio of 0.092. Completion of the test was prevented by engine failure.

2. For any attained power level the indicated specific liquid consumption was appreciable lower for the amine-water solutions than for water alone.

3. Increasing the exhaust back pressure had little effect on the knock-limited indicated mean effective pressure at fuel-air ratios between 0.05 and 0.10. For fuel-air ratios higher than 0.10, rough running and severe decreases in power output as compared with the atmospheric back-pressure test were observed.

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TABLE I - KNOCK-LIMITED RELATIVE POWERS RESULTING FROM

THE USE OF INTERNAL COOLANTS

[CFR engine; compression ratio, 7.0; inlet-air temperature, 250° F; coolant temperature, 250° F; spark advance, 30° B.T.C.; engine speed, 2500 rpm]

Internal coolant	Weight of coolant per pound of fuel (lb)	imep (fuel + internal coolant) / imep (fuel alone)					
		Fuel-air ratio[a]					
		0.05	0.06	0.07	0.08	0.09	0.10
None	----------	1.00	1.00	1.00	1.00	1.00	1.00
Water	0.25	----	1.25	1.21	1.21	1.16	1.08
	.50	----	1.48	1.48	1.37	1.24	1.13
32 percent monomethylamine-water solution	0.25	1.78	1.46	1.66	1.75	1.70	1.60
	.50	2.22	2.16	2.18	2.17	2.14	2.18
27 percent dimethylamine-water solution	0.25	1.72	1.42	1.51	1.59	1.57	1.55
	.50	1.62	1.61	2.02	2.16	2.24	2.33
	.75	1.89	1.97	2.60	2.83	3.32	----
27 percent dimethylamine-water solution with exhaust back pressure[b]	0.50	1.82	1.56	1.92	2.11	2.20	2.15

[a]Any contribution of the amines to the energy of combustion was entirely neglected in computing the fuel flows.

[b]The indicated mean effective pressure for this test (back pressure equal to half the intake pressure) is compared with the indicated mean effective presssure for a test of straight fuel (atmospheric back pressure).

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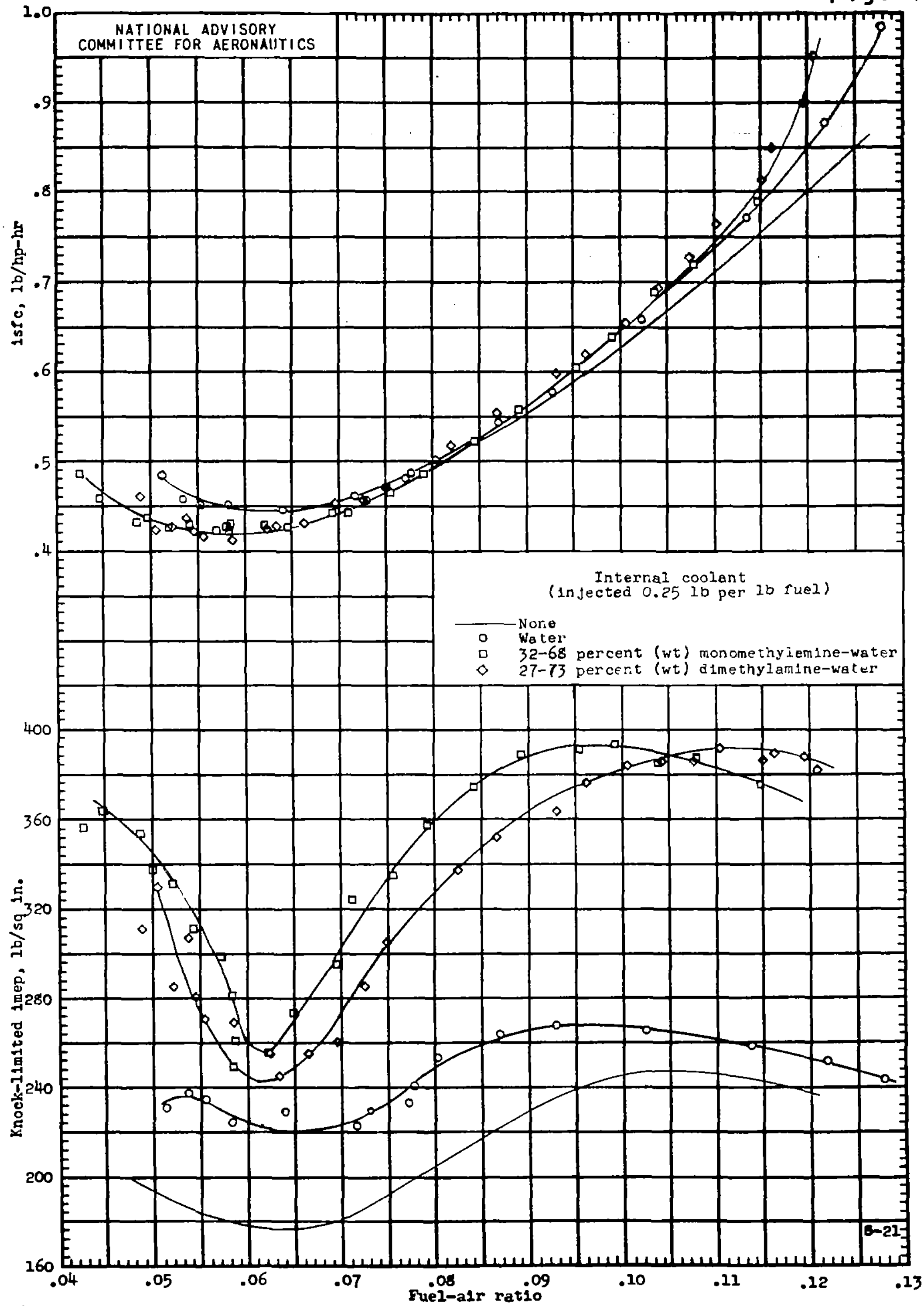
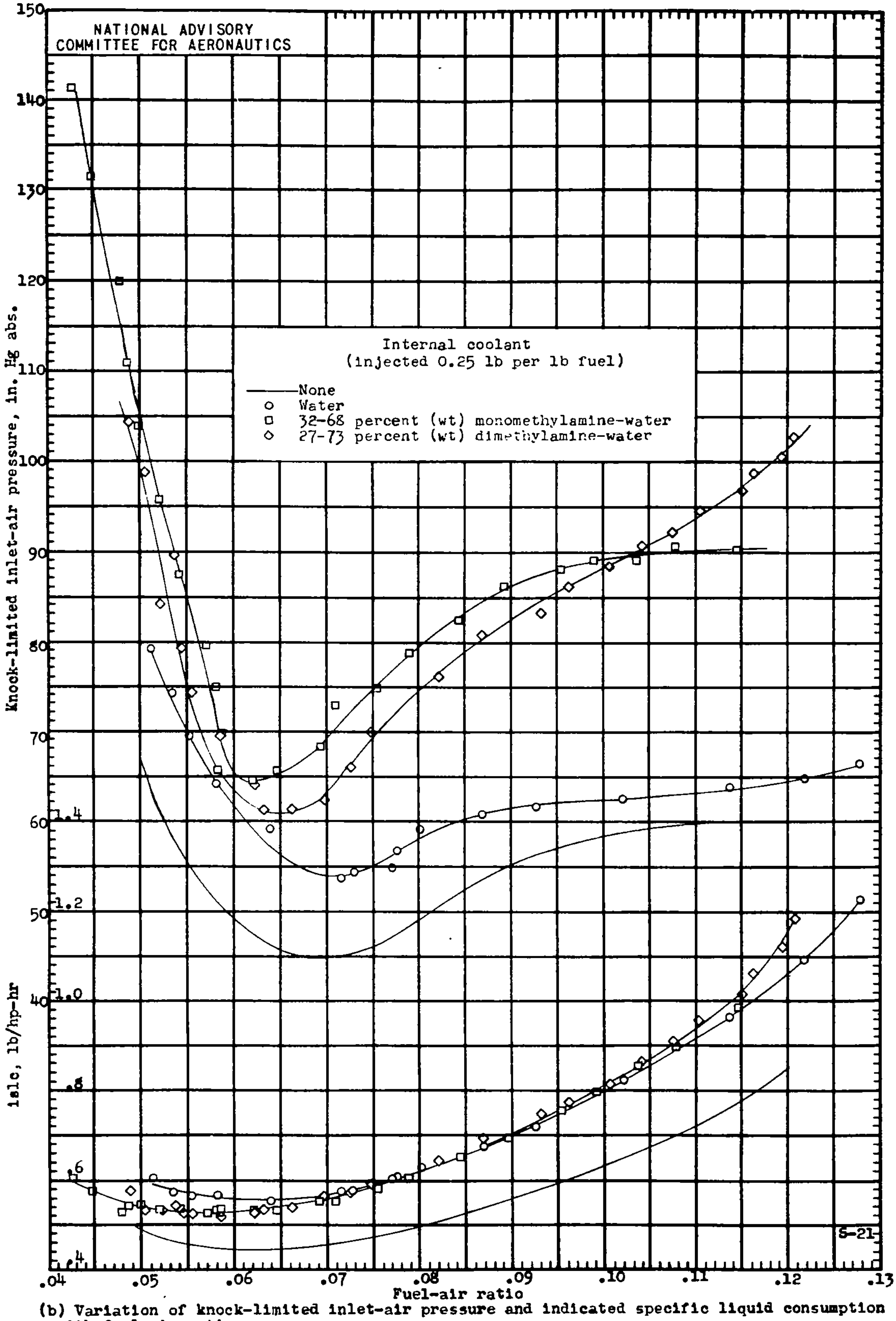
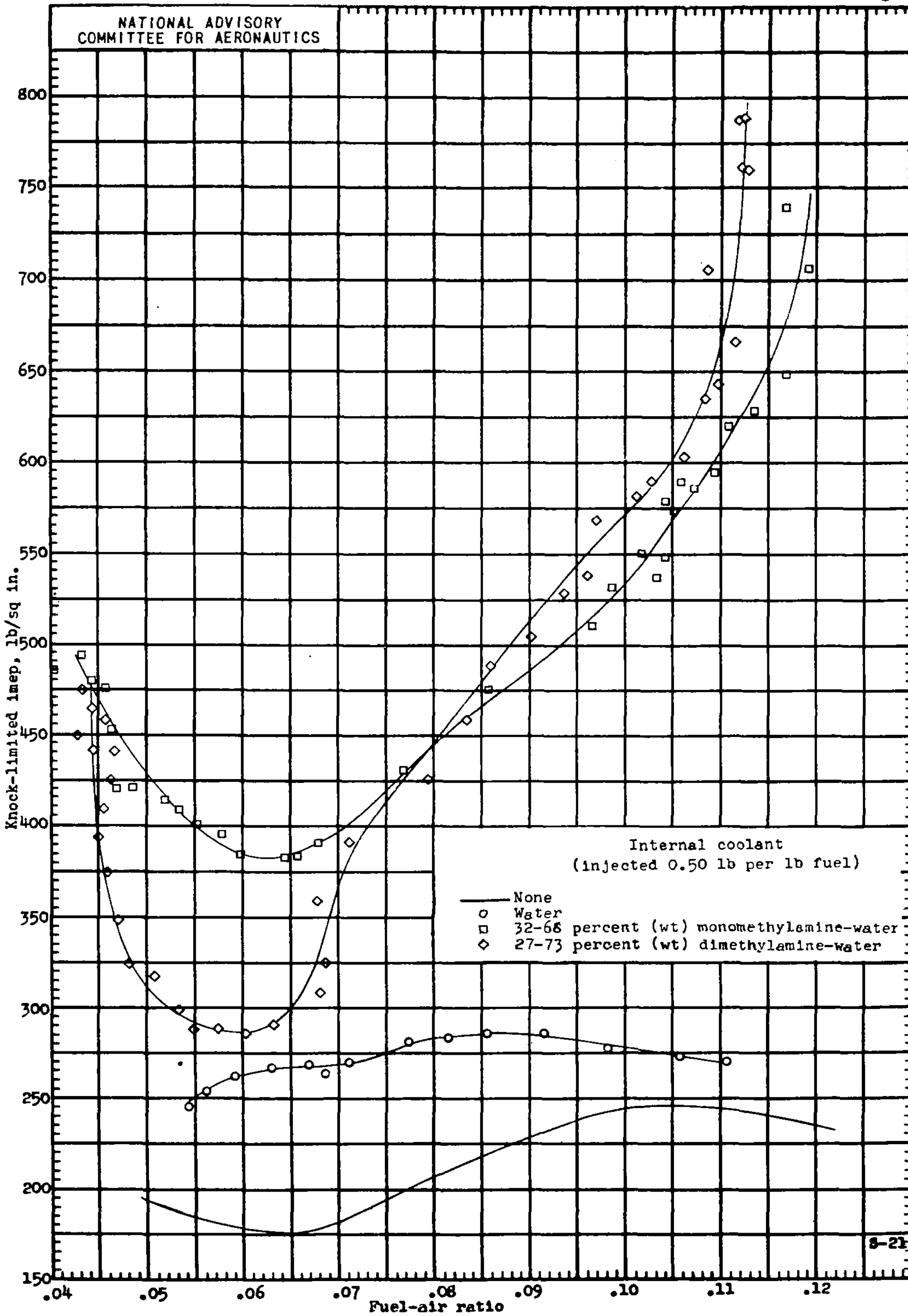


(a) Variation of indicated specific fuel consumption and knock-limited indicated mean effective pressure with fuel-air ratio.

Figure 1. - Effect of manifold injection of 0.25 pound internal coolant per pound fuel on knock-limited engine performance. CFR engine; AN-F-28, Amendment-2, fuel; compression ratio, 7.0; coolant temperature, 250° F; spark advance, 30° B.T.C.; engine speed, 2500 rpm; inlet-air temperature, 250° F.

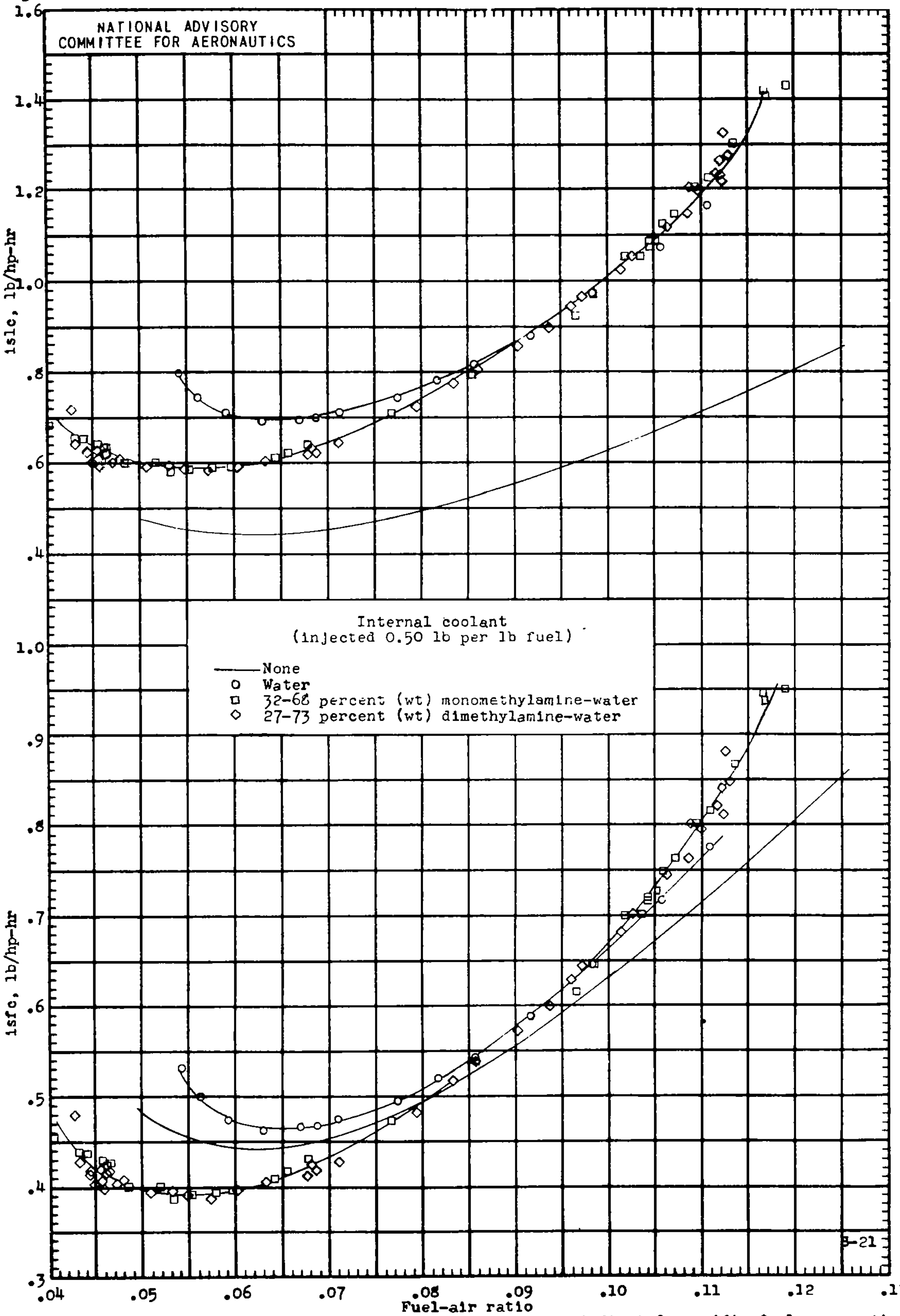


(b) Variation of knock-limited inlet-air pressure and indicated specific liquid consumption with fuel-air ratio.
Figure 1. - Concluded.

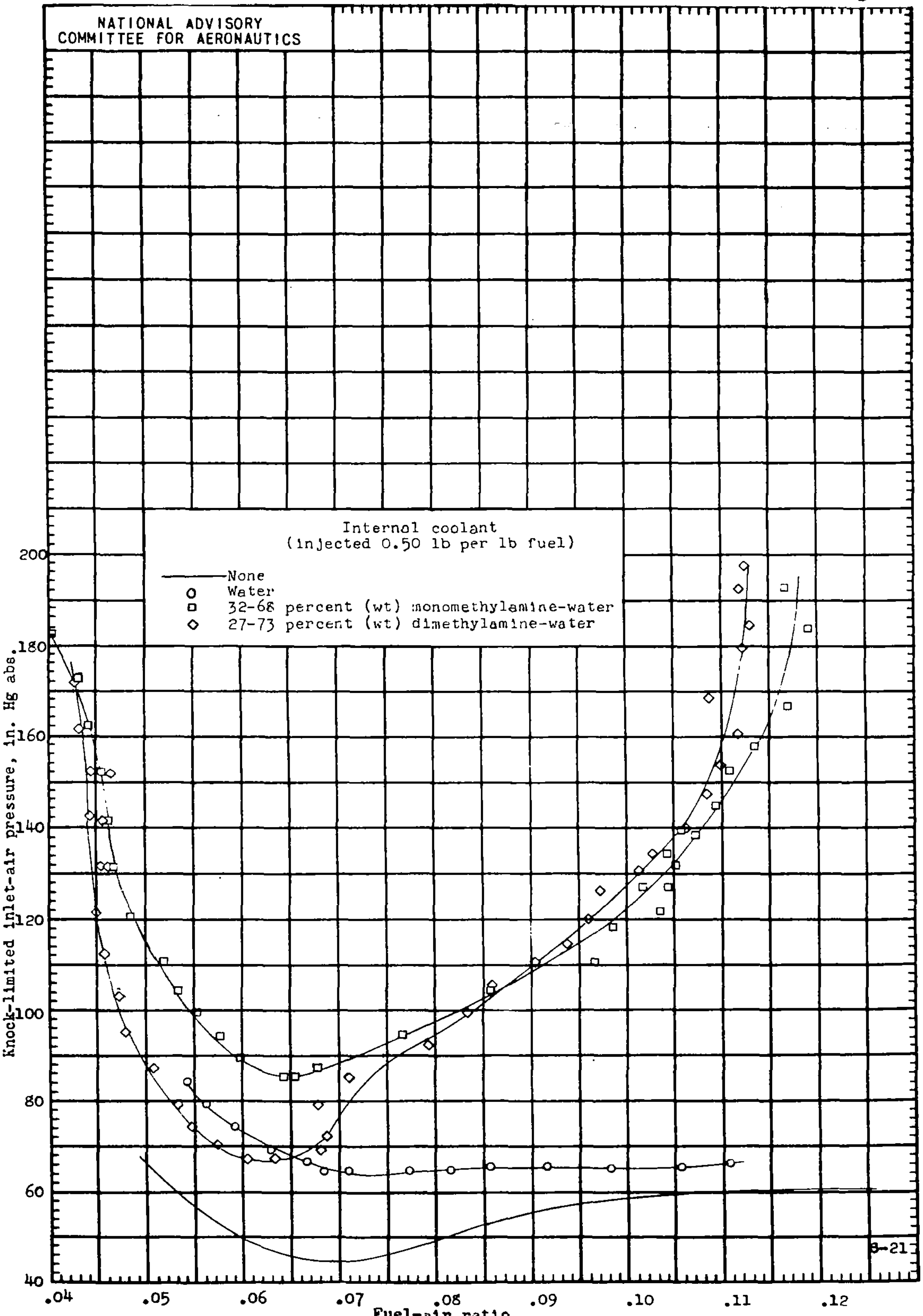


(a) Variation of knock-limited indicated mean effective pressure with fuel-air ratio.

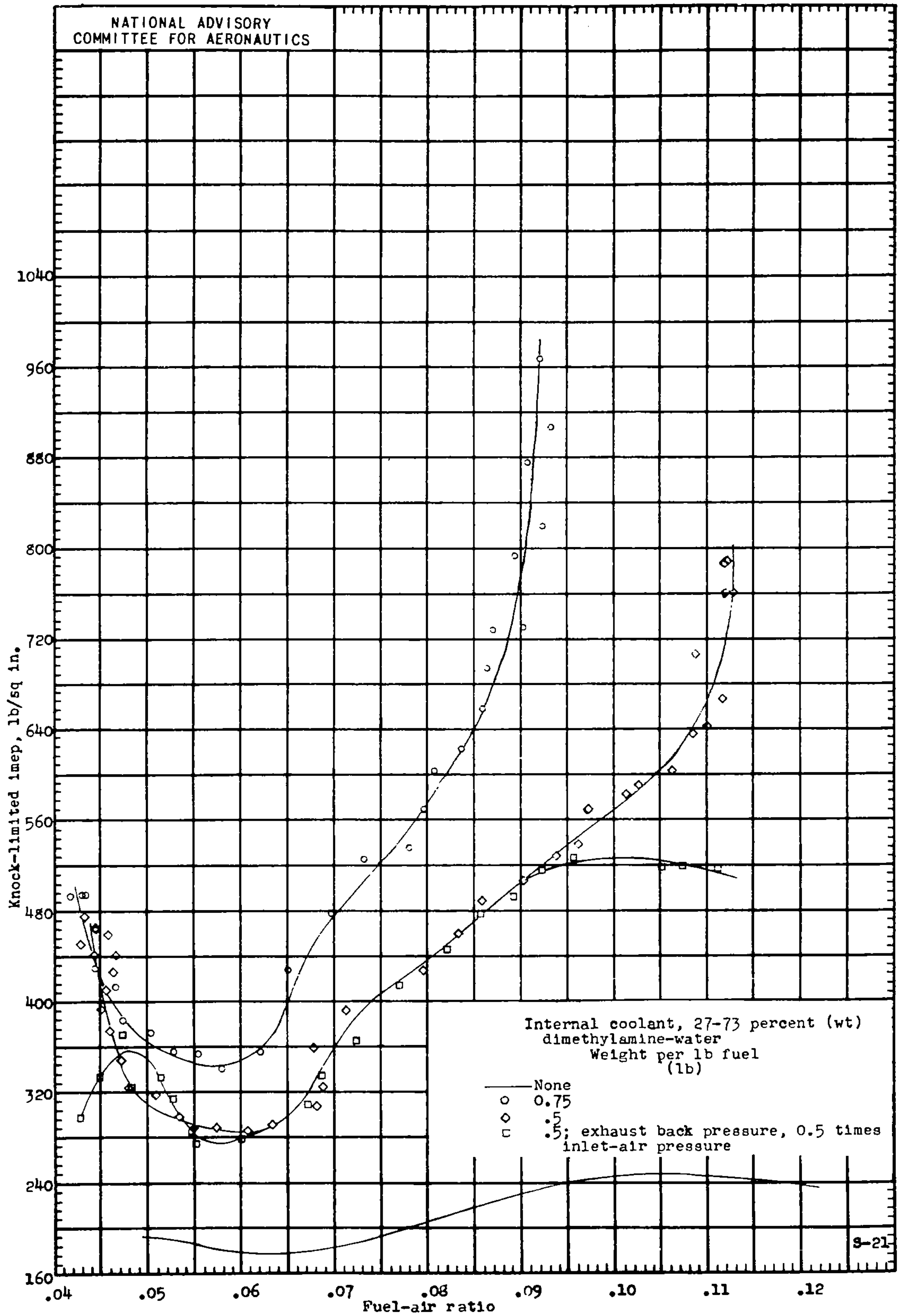
Figure 2. - Effect of manifold injection of 0.5 pound internal coolant per pound fuel on knock-limited engine performance. CFR engine; AN-F-28, Amendment-2, fuel; compression ratio, 7.0; coolant temperature, 250° F; spark advance, 30° B.T.C.; engine speed, 2500 rpm; inlet-air temperature, 250° F.



(b) Variation of indicated specific liquid consumption and indicated specific fuel consumption with fuel-air ratio.
Figure 2. - Continued.

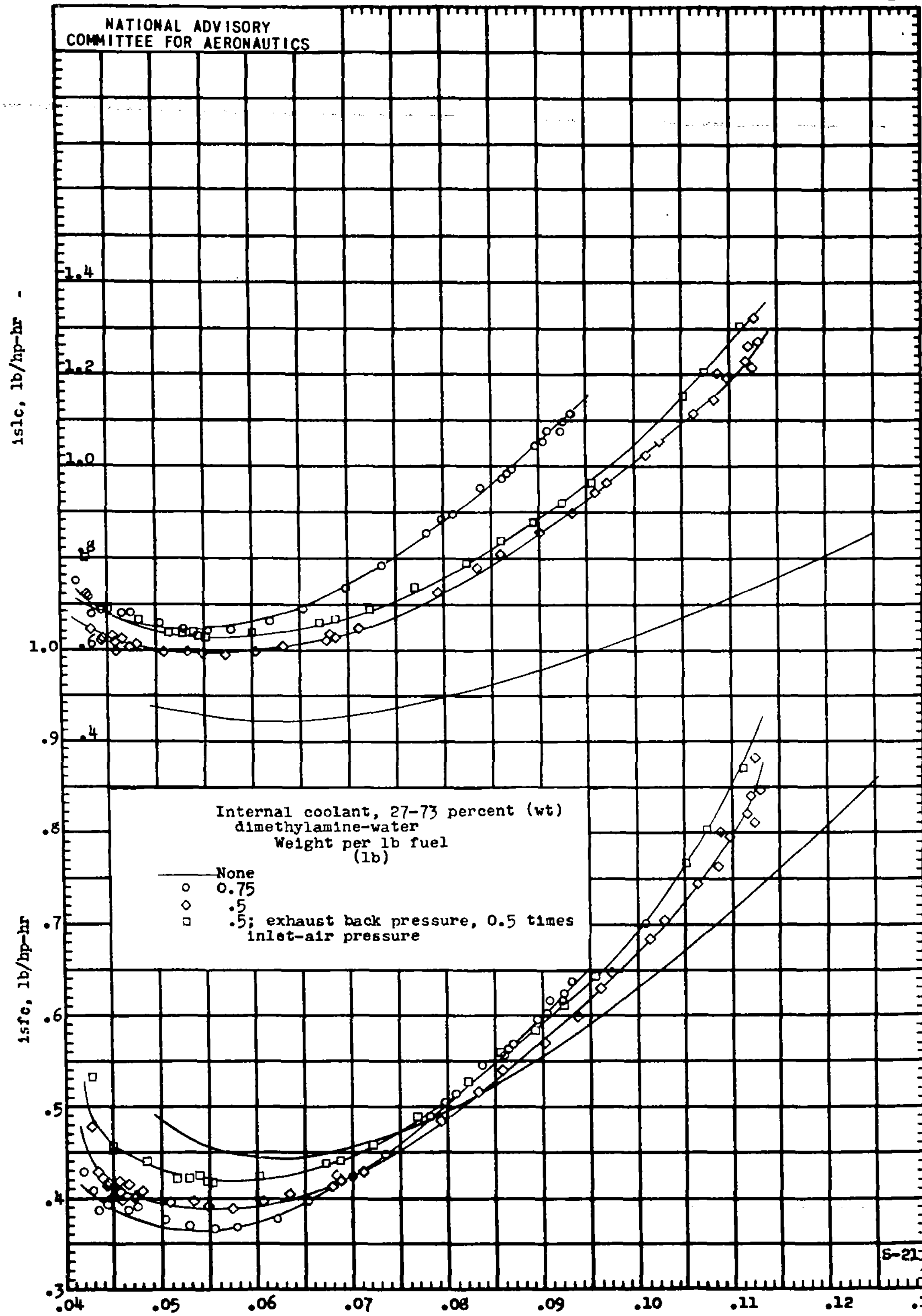


(c) Variation of knock-limited inlet-air pressure with fuel-air ratio.
Figure 2. - Concluded.



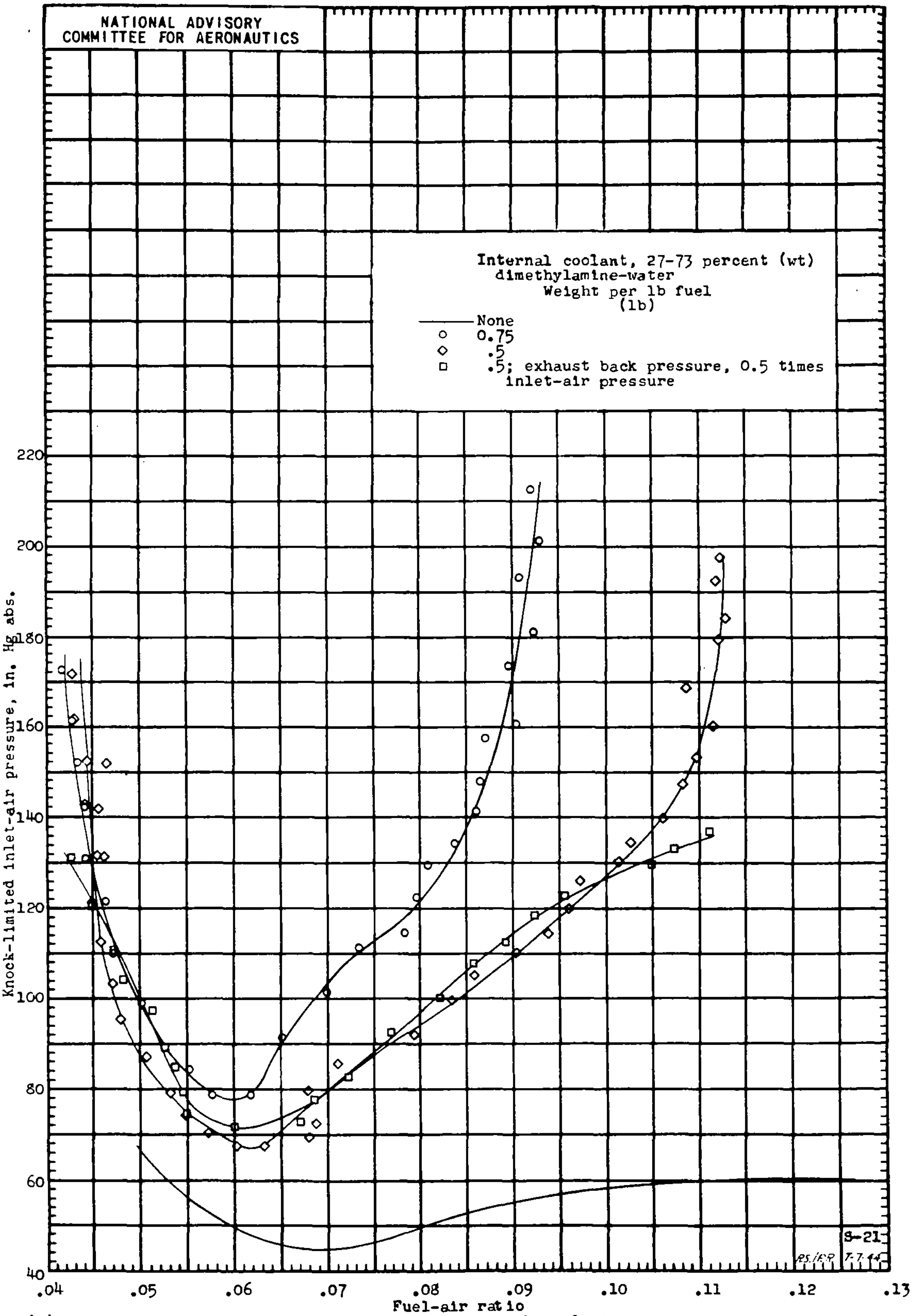
(a) Variation of knock-limited indicated mean effective pressure with fuel-air ratio.

Figure 3. - Effect of exhaust back pressure and injection of 0.75 pound dimethylamine-water solution per pound fuel on knock-limited engine performance. CFR engine; AN-F-28, Amendment-2, fuel; compression ratio, 7.0; coolant temperature, 250° F; spark advance, 30° B.T.C.; engine speed, 2500 rpm; inlet-air temperature, 250° F.



(b) Variation of indicated specific liquid consumption and indicated specific fuel consumption with fuel-air ratio.

Figure 3. - Continued.

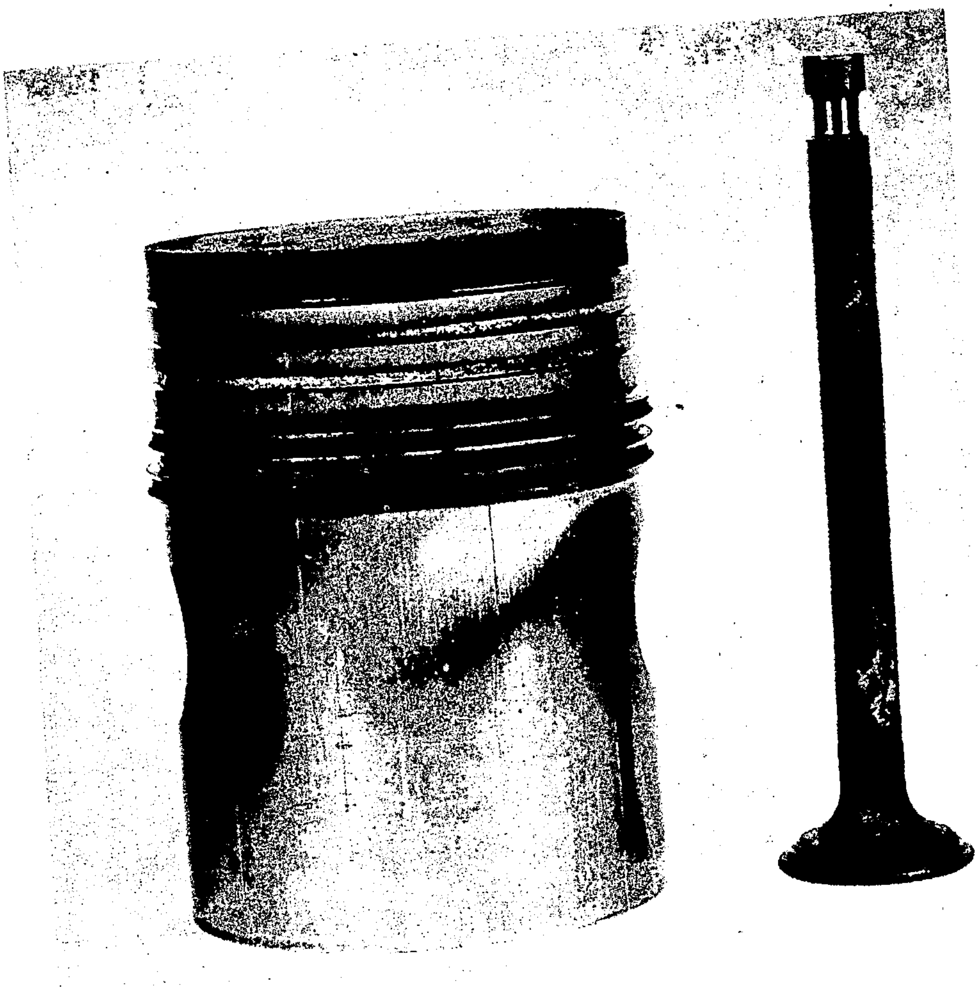


(c) Variation of knock-limited inlet-air pressure with fuel-air ratio.
Figure 3. - Concluded.

(a) Intake valve and major-thrust side of piston.

Figure 4. - Piston and valves after 55 hours of operation. Removed and photographed after engine breakdown at a knock-limited indicated mean effective pressure of 967 pounds per square inch.

Fig. 4b



(b) Exhaust valve and minor-thrust side of piston.

Figure 4. - Concluded.

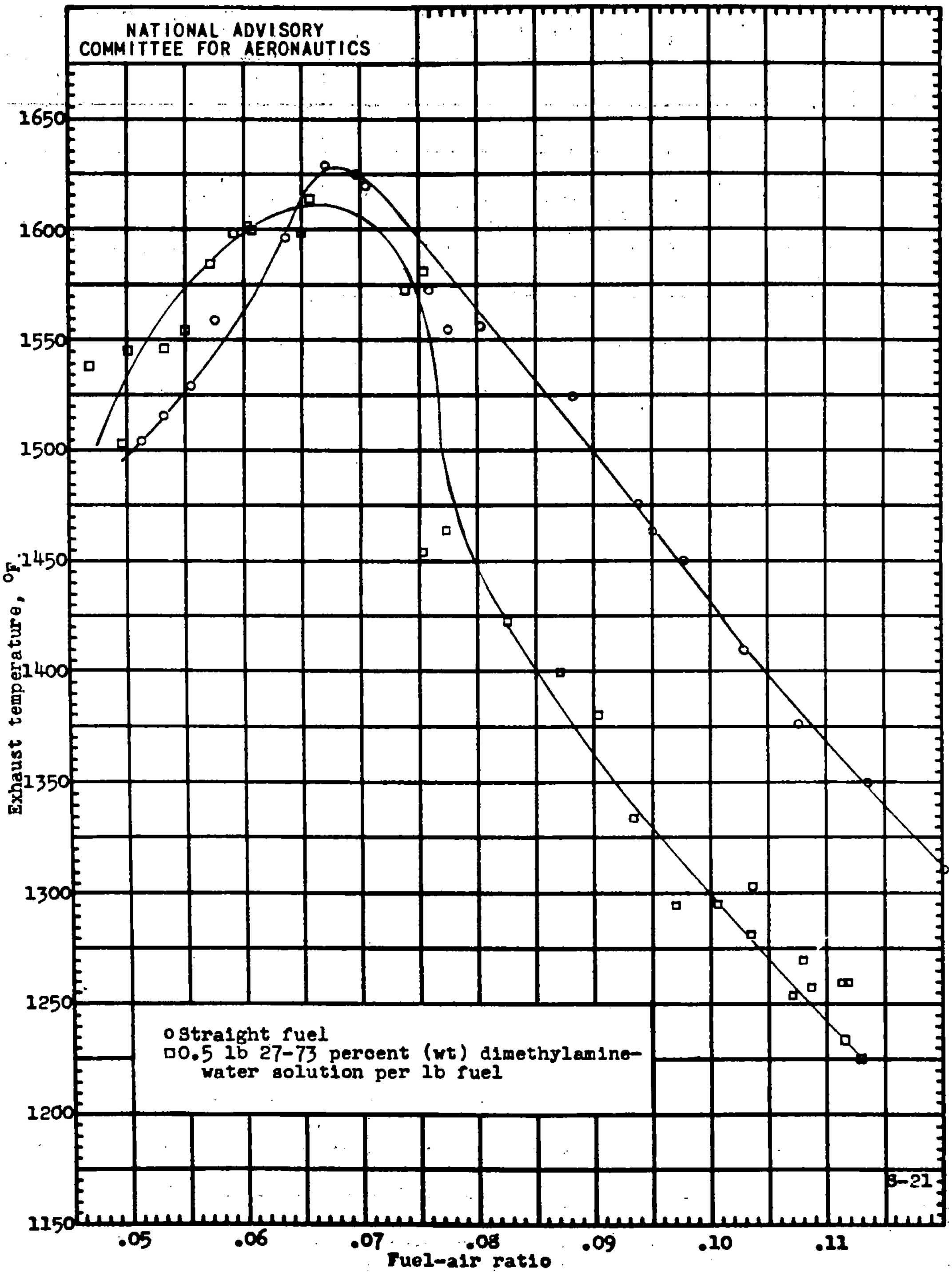


Figure 5. - Comparison of exhaust temperatures with and without internal cooling. CFR engine; AN-F-28, Amendment-2, fuel; compression ratio, 7.0; coolant temperature, 250° F; spark advance, 30° B.T.C.; engine speed, 2500 rpm; inlet-air temperature, 250° F.

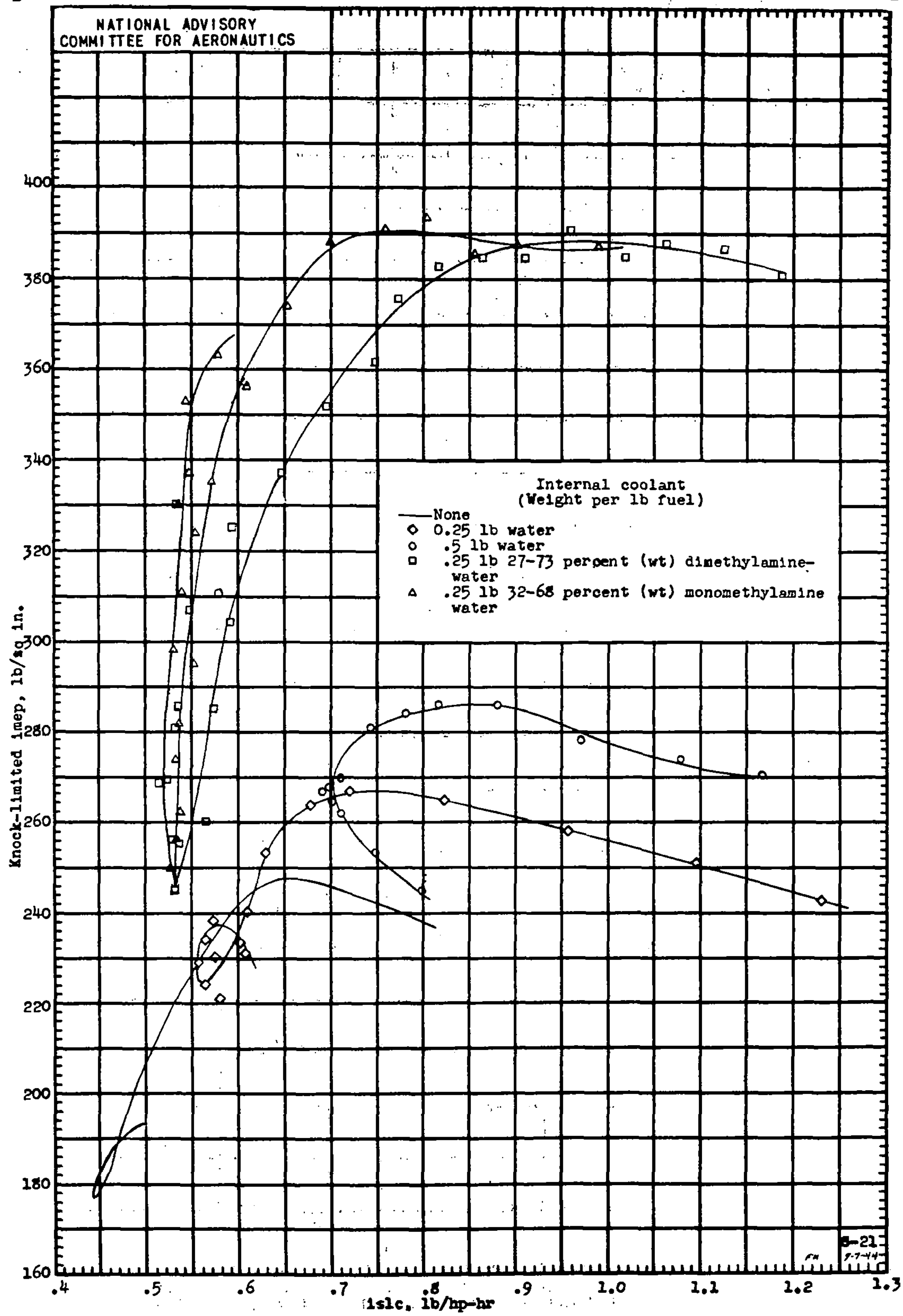


Figure 6. - Effect of internal coolants on the relation between knock-limited indicated mean effective pressure and indicated specific liquid consumption. CFR engine; AN-F-28, Amendment-2, fuel; compression ratio, 7.0; coolant temperature, 250° F; spark advance, 30° B.T.C.; engine speed, 2500 rpm; inlet-air temperature, 250° F.

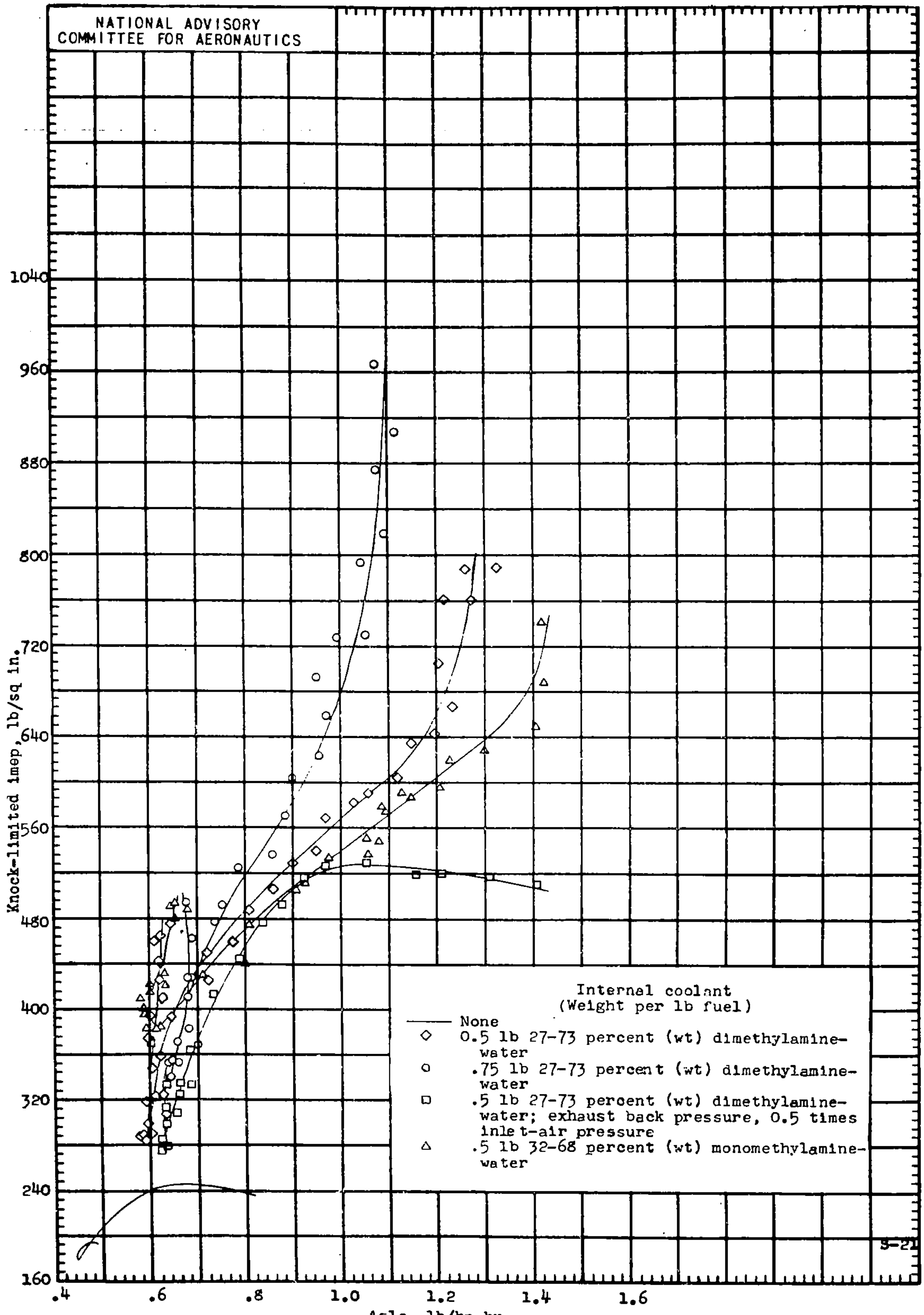


Figure 6. - Concluded.